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METAL-BASED COMPOSITE MATERIALS

by

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LASER ROLLING METHOD IN FABRICATING METAL-BASED COMPOSITE MATERIALS

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[ABSTRACT] The paper introduces the fabrication technology of FRM sheet using laser-rolling method newly announced by Japan Research Group. The main parameters of the fabrication process and the effect of the forming conditions on FRM sheet properties are emphatically discussed in this paper.

KEY WORDS: Fiber-reinforced metal-based composite materials, forming technique, laser beam, rolling.

I. Background

With continuous development of aeronautics and astronautics activities, more and more lightweight, large unit-size and long-service-life structural materials are required. Metal-based composite materials have excellent material properties; this is a new aeronautical and astronautical class of structural materials, heralded as twenty-first-century new materials, developed from resin-based composite materials. This is a product of the third material revolution. At the Twenty-First Century Composite Materials Consortium of Research and Development in Japan, while

in the materials research transition from the laboratory to the fundamental application research, great enthusiasm greeted research on manufacturing and forming techniques. Various types and shapes of metal-based composite materials are being studied and fabricated. The forming technique, such as pressing and forming, rolling and forming, as well as thermostatic pressure are among the techniques under study.

Generally, forming of metal-based composite materials should be done at high temperatures and high pressures. With adoption of the hot press machine with the thermostatic compression forming method, the forming of a canopy for large structural members should require vast sums in investment for gigantic equipment. Second, by using metal-based composite materials to replace metals when fabricating lightweight structural members, the specific strength and specific rigidity are also superior to metal members, thus reducing the cross-sectional area. Therefore, within the allowable range of machining for materials used in aeronautical and astronautical members, there are many occasions that require metal-based composite thin plates of less than 0.5mm thickness. However, the forming technique is not simple. Under this technical background, it is an important research topic to satisfy the aeronautical and astronautical materials by using metal-based composite materials in large and thin plate forming techniques.

Laser beams, electron beams, and other high-energy beams have the capability of heating and irradiating highly precisely

on a unit area. Most processing systems used in production with a high degree of control apply welding and cutting of metal-based composite materials. At the Twenty-First Century Composite Materials Consortium of Research and Development in Japan, researchers discovered, upon studying the weldability of metal-based composite materials with laser beams, that the strengthening fibers and the matrix do not have violent reaction when the matrix metal is being melted while being irradiated with a laser. Moreover, when a high-energy-density laser beam is used to irradiate the material surface, it will be rapidly heated. Thus, the laser beam processing technique is successfully applied in forming thin plates made of metal-based composite material. A new technique was developed with laser rolling and forming of metal-based composite materials. Thus, laser beams are used as the heating source and the rolling wheel is used as the pressing mechanism to form the entire member in one process at high temperature and pressure. This laser rolling and forming technique can be used to solve the major technical problems of continuous forming of thin plates in large aeronautical and astronautical structural members.

II. Principle and Features of Laser Rolling and Forming Technique

In the experiment, the forming technique of thin plate-shaped metal-based composite materials involved prefabricated filaments. Fig. 1 shows the forming principle. Just before being rolled, the prefabricated filaments are irradiated with a

laser to have its temperature raised to the joining requirements. At the high-temperature state, the prefabricated filaments are rolled, pressed, and deformed, thus tightly joining to the matrix

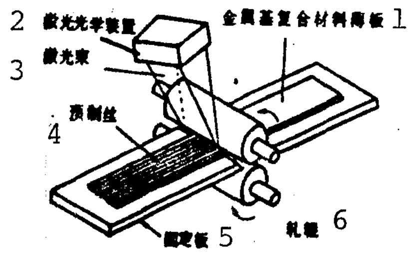

图1 激光辊轧成形技术原理

Fig. 1. Principle of laser roll forming technique
KEY; 1 - metal-based composite material thin plate
2 - laser optics apparatus 3 - laser beam
4 - prefabricated filaments 5 - platen 6 - roll

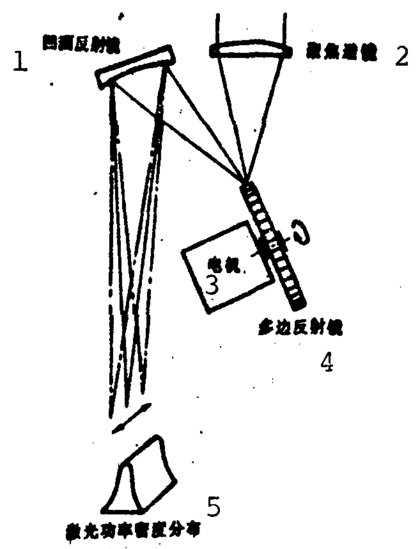

Fig. 2. Polygonal reflective mirror scanning system
KEY: 1 - concave surface reflective mirror
2 - focusing lens 3 - electric motor 4 - polynomial reflective mirror 5 - distribution of laser power density

material. During the experiments, a 10.6μm (in wavelength) CO_2 laser (at a maximum upper power of 5kW, scanning through a

polygonal reflective mirror, as shown in Fig. 2, to obtain a linear laser beam along the widthwise direction of the fabricated filament arrangement. The laser beam is homogeneous in power density.

The unique features of laser rolling and forming technique is a continuous forming by local heating and local pressing on the material. Since the irradiating position of the laser beam can be easily controlled in three dimensions, only by making some effort on the pressing mechanism, can continuous forming be executed without the limitation of shape. From the view of local sites, forming is accomplished in a very short time period under high temperature. The heating and cooling rates are higher than 1000K/s, thus restraining the undesirable effects of heat to the maximum extent. Therefore, the adoption of a high-energy-density laser beam to heat the specimen surface is an effective heating method in forming thin plates made of metal-based composite materials.

III. Discussion of the Main Factors Affecting Forming Technique

1. Effects due to materials

To easily use laser welding to join filaments to matrix metal in order to form a thin plate, during this experiment of exploring the laser rolling and forming technique, an intermediate material, prefabricated filaments, is applied to properly treat the fibers and matrix metal. The following table lists the types of aluminum-based prefabricated filaments.

During the experiment, by determining the absorption rate for various material surfaces with respect to irradiation by a laser, the heating effects on the prefabricated filaments of a laser beam was estimated. Generally speaking the absorption rate of aluminum with respect to a laser is only 3% for a 10.6μm

TABLE. Types of Prefabricated Filaments

1 符号	2 纤维		5 基体	抗拉强度(GPa) 6
	3 材料	商品名 4		
SiCpcs/1050	SiCpcs	Nicalon	A1050	1.0
SiCcvd/6061	SiCcvd 7	Scs-2	A6061	1.7
M40J/1080	HM-C(聚丙烯腈基)	M40J	A1080	1.4
P100/6061	HM-C(沥青基) 8	P100	A6061	0.6

KEY: 1 - symbol 2 - fiber 3 - materials 4 - commercial name 5 - matrix 6 - tensile strength 7 - polypropyl base 8 - asphalt base

wavelength CO_2 laser. However, the absorption rate with respect to a laser is increased to 12% by silicon carbide fiber monodirectional strengthening aluminum-based prefabricated filaments SiCpcs/1050. Based in investigation reports on the absorption rate of a laser by carbon fiber aluminum-based composite material, it was found that the rate can be as high as 30%. This is because, after the grinding of the surface, the laser absorption rate is very high for the bare carbon fibers. However, for SiCpcs/1050 prefabricated filaments, the surface has been covered with aluminum so the reason for the rising absorption rate cannot be explained with the surface constituents. However, the concave and convex irregular shapes on the fiber surfaces of the SiCpcs/1050 prefabricated filaments

is the main reason for the higher absorption rate. For a thicker surface and smoother aluminum surface layer with carbon fiber-strengthened aluminum base (P100/6061), the laser absorption rate for prefabricated filaments is only one-third that of SiCpcs/1050. For metal-based composite material flat plates with surface aluminum properties basically equal to those of aluminum, its laser absorption rate is the same as that for pure aluminum. Therefore, the material composition and surface geometric shapes (under laser irradiation) have a great effect on the laser absorption rate. By fabricating the matrix metal and the reinforcing fibers into the prefabricated filaments, the heating effect of the matrix material due to the laser beam can be improved.

2. Pretreatment

Control of surface treatment, layout and shape of the prefabricated filaments are within the pretreatment range, which also includes the addition or change in fiber content (v_f) in the prefabricated filaments by matrix metal. These factors are not discussed here at length. In research on laser rolling and forming technique, the prefabricated filaments are arranged monodirectionally and tightly. Rolling takes place in the fiber axial direction in order to have continuous forming of thin plates.

3. Effects due to laser irradiation conditions and rolling speed

In the laser rolling and forming technique, the laser irradiation conditions and the rolling speed are a pair of correlated functions, jointly affecting the temperature change at the metal surface during forming. Fig. 3 indicates this influence mode. The metal is fed into the space between the rolls and is heated in region II during laser beam irradiation. Actually, the temperature begins to rise slightly ahead of the

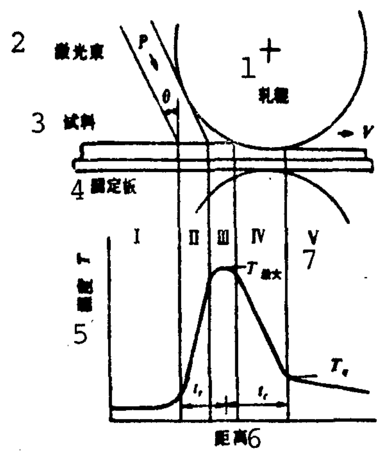

Fig. 3. Temperature variations of material in the process of laser roll forming
KEY: 1 - roll 2 - laser beam 3 - test materials 4 - fixed platen 5 - temperature 6 - distance 7 - T_{max}

position being irradiated with the laser beam. This is because the heat conduction and the laser beam in the high-temperature region are not an ideally straight line. Upon entering the laser irradiation region II, the temperature rises rapidly. The temperature reaches its maximum in region III. In region IV, as the rolling pressure is in effect, the surface rapidly cools down. From Fig. 3, the width of region III is determined by the

laser irradiation angle, the press roll, and the geometric shape of the irradiated workpiece. If the irradiated angle Θ is increased to almost allow region III to become zero, then the material can be under irradiation by the laser beam just prior to entering the space between the rolls. Thus, the temperature of the material beginning to be rolled is equal almost to the highest temperature attained by the material. This temperature is the most important parameters in the forming technique, as mainly affected by the laser irradiation power and the rolling speed. In Fig. 4, when the laser irradiation power is kept at 400W, and the rolling speed is varied within the range 10 to

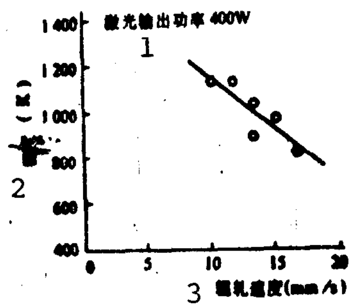

Fig. 4. Maximum temperature of prefabricated filaments in the process of laser roll forming
KEY: 1 - laser output power 2 - temperature
3 - rolling speed

17mm/s, the temperature is shown for the SiCpcs/1050 prefabricated filaments. This temperature is inversely proportional to the rolling speed. This can be qualitatively explained by the fact that the energy absorbed by the material is proportional to the irradiation time of the laser irradiation power multiplied by the absorption rate.

However, the highest temperature attained is not entirely

determined by the laser irradiation power and rolling speed; this is markedly related to the distribution state of laser power density, laser irradiation position, gap between the rollers, and the irradiation angle. Considering from the viewpoint of temperature control, it is expected to reduce the geometric width of the laser beam in the rolling direction in order to obtain the ideal straight beam. With respect to materials, the rolls correspond to a cooling source. The closer the distance between the laser irradiation position to the roll, the closer is the highest attainable temperature of the material from the laser irradiation region II, then the highest temperature attained will have a downward trend. It is clarified that the irradiation angle also has an effect on the highest attainable temperature. This also suggests that there is a different absorption rate of materials to the laser with the different laser irradiation angle.

From Fig. 4, the feasible condition of thin plate forming of the SiCpcs/1050 aluminum based composite material is when the rolling speed is between 13 and 15m/s. At this point, the highest temperature attained by the prefabricated filaments is 950K, which is slightly higher than the melting point of the matrix metal. However, the highest temperature reached in Fig. 4 is the highest value of the surface temperature of the prefabricated filaments observed with a pyrometer.

Within this range of forming conditions, the highest temperature attained by the prefabricated filaments is measured

when the filament volumetric content (v_f) is 0.4. When v_f is 0.3, the highest attainable temperature is 750 to 850K. This temperature also indicates that the main regime of joining prefabricated filaments is solid-phase thermal joining during forming by laser rolling.

IV. Effect of Properties for Forming Body by Forming Conditions

In the experiment, an investigation was conducted in which thin-plate forming was carried out with SiC fiber (Nicalon) and carbon fiber (M40J) unidirectional reinforced aluminum-based prefabricated filaments, to discover the effect on the technical parameters (such as joining rate, porosity, and mechanical properties) of the final forming body affected and the range of forming conditions.

1. Joining Rate

By using the cross section of an SiCpcs/1050 thin plate after laser roll forming observed with an optical microscope, it was discovered that the rolling speed is increased and the heat absorption by material is decreased when the laser output power is constant (400W), and within the rolling speed variation range (10 to 17mm/s), thus leading to a lowered joining effect. When the speed is 17mm/s and there are unjoined regions among the fibers, the reduction of rolling speed can obviously improve the joining status among fibers. When the rolling speed is less than 13mm/s, no unjoined regions were discovered cross-sectionally.

Fig. 5 shows the results of the effect for the joining rate of the metal-based composite material thin plate after forming with respect to rolling speed. When ten prefabricated filaments were arranged to carry out forming, apparently we can observe that there are different joining rates among fibers in the middle and fringe portions of the thin plate. The closer from the fringe portion, the lower is the joining rate. Upon comparing the joining rate obtained by the six middle prefabricated filaments, and the entire ten prefabricated filaments, the joining rate of the former is twice that of the latter. However, their joining rate has a declining trend with increase in rolling speed.

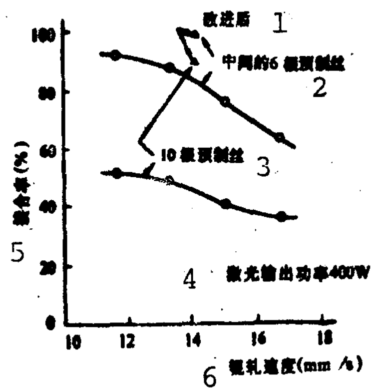

Fig. 5. Effect on joining rate of SiCpcs/1050 thin plate with respect to rolling speed
KEY: 1 - after improvement 2 - six middle prefabricated filaments 3 - ten prefabricated filaments 4 - laser output power 5 - joining rate 6 - rolling speed

Besides, the joining rate is also related to the fiber volumetric content (v_f) in the prefabricated filaments. Reduction of the v_f is advantageous to improving the thin plate joining rate. Some matrix metal is added to the original

SiCpcs/1050 prefabricated filaments with v_f at 0.36, so that v_f is reduced to 0.3. Then the joining rate of thin plate forming is shown by Δ in Fig. 5. By changing the v_f value, the joining rate of the middle six prefabricated filaments can rise to 98% (the joining rate of all the ten filaments is 88%).

2. Porosity

Fig. 6 shows the flaw evaluation result of the SiCpcs/1050 prefabricated filaments. The so-called flaw generally consists of fiber breakage, stripping of boundary surface, and the growth of cracks. By referring to the research report on gas voids produced during laser welding of metal-based composite

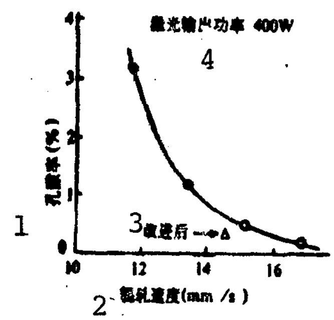

Fig. 6. Effect on porosity of SiCpcs/1050 thin plate with respect to rolling speed
KEY: 1 - porosity 2 - rolling speed 3 - after improvements 4 - laser output power

material, this experiment shows the flaw evaluation of area rate of the voids cross-sectionally. From Fig. 6, when the rolling speed is higher than 15mm/s, porosity and cracks rapidly decrease. When the rolling speed is 16.7mm/s, the porosity has decreased to 0.2%. Conversely, once the rolling speed slows down, voids are formed. When the rolling speed is 11.7mm/s,

inside the thin plate there are not only the occurrence of multiple voids in the thin plate, but concave depressions are also observed on the surface of the thin plates. Meanwhile, in the aluminum-rich regions, excrescences were also observed. As explained by these results, flaws of the forming body increase with slowing down of the rolling speed, and increase of absorption heat. In Fig. 6, Δ is the porosity of the SiCpcs/1050 when v_f is 0.3.

The effect on joining rate and porosity of the carbon fiber reinforced aluminum-based composite material by the forming conditions has the same trend as SiCpcs/1050. However, when the carbon fiber aluminum-based composite material is formed, voids form more easily. By increasing the metal matrix content in the prefabricated filaments, there can be fewer voids. With respect to forming M40J, if the v_f value is decreased from 0.46 to 0.4, under similar forming conditions, the joining rate of the middle six fibers can be increased from 80% to 100%.

3. Mechanical Properties

By using elongation tests on the formed SiCpcs/1050 and M40J/1080 thin plates, and evaluating the mechanical properties along the fiber direction, as discovered in the results, comparison with the prefabricated filaments shows that the elongation properties of the SiCpcs/1050 and M40J/1050 thin plates are reduced to differing extent. The specific strength and the specific elasticity of the SiCpcs/1050 thin plates are,

respectively, over 0.7 and 0.9. However, the mechanical properties of M40J/1050 thin plates are even further reduced. The specific strength and specific elasticity are only 0.3 and 0.7. As discovered by observing the appearance of elongation notches of the SiCpcs/1050 thin plates, the notch is relatively flat; however, the notch in prefabricated filaments appears uneven. For further exploration of the cost of reduced mechanical properties, with laser irradiation on SiCpcs/1050 filaments, it was discovered that when the surface temperature of the test material was less than 1150K, the elongation strength basically remained constant. When the surface temperature rose to more than 1150K, the elongation strength radically declined. After heating the test materials at 1250K, it was discovered in x-ray microanalysis (EPMA) that elemental silicon exists in the matrix element, and carbon exists in very close proximity to the fibers. After further heating the test material to 1800K, this phenomenon is more obvious. By using EPMA, it was determined that radiating silicon excretes from the matrix aluminum. Meanwhile, the diameter of the SiCpcs fiber became one-half of the preheating value. By using x-ray diffraction, we also discovered that there exist silicon and AlC_3. This illustrates that the final deterioration of the mechanical properties of the prefabricated filaments is due to reaction between matrix metal and fibers during forming. Controlling the surface temperature of the test material during forming so that it is below the critical value that causes the decline in mechanical properties,

the properties of the prefabricated filaments can be improved.

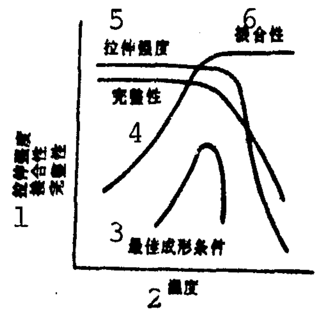

Fig. 7. Optimal forming conditions of laser roll forming technique
KEY: 1 - tensile strength, joining property, integrity 2 - temperature 3 - optimal forming conditions 4 - integrity 5 - tensile strength 6 - joining property

From the viewpoint of the highest temperature attained for material during forming, investigate the optimal forming conditions of the laser roll forming technique. As shown in Fig. 7, the relationship among the joining properties, integrity, and mechanical properties of the prefabricated filaments should be regarded as a whole. However, the possible condition of thin plate forming is that the highest heating temperature of the material surface should be slightly higher than the melting point of the matrix metal. The integral solid-phase pressure joining is the main forming regime.

V. Conclusions

By discussing the prefabricated filament forming of 0.45mm thin plate on the effect by forming conditions on the thin plate forming rate, porosity, mechanical properties, and other

properties, we can realize that the laser roll forming technique is a means suitable to forming of metal-based composite materials. It is feasible for forming fiber-reinforced metal-based composite material thin plates. As for the cause of declining mechanical properties of the fiber-reinforced metal-based composite material after its forming, in the present viewpoint it is very possibly due to damaged fibers. Therefore, it is still necessary to further explore in detail the technical parameters of the laser roll forming technique in order to find the optimal forming conditions, especially in research on laser roll forming technique with carbon fiber-reinforced metal-based composite material.

At present, the laser roll forming technique has not been perfected. One of the later developments is to establish a flexible manufacturing system.

Compiled and translated from "Laser Rolls: Composite Material Technology in the Next Century", published September 1990.

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